A Novel Two-Level Fast Mixed Load Flow Algorithm for Multi-Area Power Systems.

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ABSTRACT

An efficient load flow solution technique is required for taking various control and operations decisions. This paper presents an efficient and robust load flow algorithm for application to transmission and distribution networks. In order to face keen competition in market, the coordinated operation between transmission and distribution systems is required. Therefore, the transmission and distribution systems are studied as a whole in this paper.

A novel master slave splitting (MSS) iterative method is developed for solving the hybrid mixed load flow (MPF) problem. In the proposed method, with introducing the boundary fictitious values, the MPF problem of large scale is split into a transmission and lots of distribution sub-problems. As the size of matrix used is very small compared to those in conventional methods, the amount of memory used is very small, the speed is very high, and the relative speed of calculation increases with the size of the system. In order to fit the different features between transmission and distribution networks, each sub-problem can be solved with different algorithms. The algorithm proposed in this paper is a “novel but classic” technique. Several case studies are carried out, and the accuracy, convergence, efficiency and reliability of the proposed method are validated.

(Keywords: load flow, transmission system, distribution system, master slave splitting, MSS)

INTRODUCTION

Load flow is an important tool for the analysis of any global power system. A real global power system is an integration of transmission and distribution systems; therefore, the interaction between the transmission and distribution systems should be considered in operation, and great benefit can be derived from global coordinated control between transmission and distribution systems, especially with the rapid development of distributed generation in the distribution network [1]-[2]. Almost all the transmission control centers have equipped with EMS [3]-[5], and many distribution control centers have also equipped with DMS [6]-[7].

In these computer systems, transmission and distribution networks have already been modeled in detail, and load flow can be done for transmission system and distribution system respectively even under real time environment. WAN[1] based communication technology is widely applied to power systems and is available for the rapid communication between EMS and DMS. Considerable research has already been carried out in the development of computer programs for load flow analysis of large global power systems, such as Digsilent [8], Neplan [9], PSAT [10] and etc. Such a load flow methods must be able to model the special features of transmission and distribution systems in sufficient detail. The well-known characteristics of an electric distribution system are:

- Radial or weakly meshed structure;
- Multiphase and unbalanced operation;
- Unbalanced distributed load;
- Extremely large number of branches and nodes;
- Wide-ranging resistance and reactance values.

Those features cause the conventional load flow methods used in transmission systems, such as the Gauss-Seidel and Newton-Raphson techniques, to fail to meet the requirements in both performance and robustness aspects in the

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[1] - Wide Area Network

distribution system applications. In particular, the assumptions necessary for the simplifications used in the standard fast-decoupled Newton-Raphson method [11] often are not valid in distribution systems. Therefore, a novel mixed load flow (MPF) algorithm for global power systems is desired.

In order to implement a global coordinated operation and control, MPF aiming to build a consistent real time model for the whole transmission and distribution systems should be studied at first. Here we orient to a more general MPF problem, of which the important characteristics are listed as follows:

(1) The size of the global power system is tremendous. For a typical medium size system, for example, assume that the number of 132 kV nodes of a transmission network is 200, including 150 load nodes. If each load node has 20 medium voltage feeders and each feeder has 10 distribution nodes on average, then the total number of nodes in the global power system will reach over 30,000.

(2) The transmission and distribution systems differ in voltage level, network topology structure, parameter of element, modeling. Therefore, each of them needs its own suitable algorithm. For instance, Newton-Raphson load flow algorithm is fit for transmission systems [12], while the forward/backward sweep technique is fit for radial distribution systems [13].

(3) The models for transmission and distribution networks are always built and maintained in geographically distributed EMS and DMS respectively, which requires the algorithm supporting geographically distributed computation. In order to develop an efficient algorithm for the distributed computing, communication and computing should be fast enough. On the other hand, the proposed algorithm should be compatible with load flow program in existing EMS and DMS.

Therefore, based on the master–slave-typed physical feature of the global power system, a novel MSS method with rigorous mathematical foundation is developed to solve the MPF problem in this paper. The algorithm proposed in this paper is a “novel but classic” technique.

BASIC THEORY

Many programs of real-time applications such as network optimization, Var. planning, switching, state estimation, and so forth, require a robust and efficient load flow method. Such a load flow method must be able to model the special features of transmission and distribution systems in sufficient detail.

According to the above characteristics, The transmission and distribution systems differ in voltage level, network topology structure, parameter of element, modeling. Therefore, each of them needs its own suitable algorithm. If a single algorithm is adopted to solve the MPF, for the remarkable diversity between the transmission and distribution systems, it is difficult to ensure simultaneously the numerical stability and computational efficiency. Therefore, a hybrid method for MPF is needed to satisfy simultaneously both the requirements of the transmission and distribution systems.

Load flow in Transmission Systems: In the last few decades, efficient and reliable load flow solution techniques, such as: Gauss-Seidel [14], Newton-Raphson [12] and Fast decoupled load flow [11], have been developed and widely used for transmission system operation, control and planning. In the proposed MPF algorithm, the transmission system is solved by the Newton-Raphson load flow method.

Load flow in Distribution Systems: Load flow analysis is a basic function in modern distribution management systems (DMSs) [15]. In literature, many methods and solving algorithms have been proposed for distribution load flow analysis. They can be essentially classified into three categories: direct methods [16]-[17], backward/forward sweep methods [13], [18]-[21], and the traditional Newton-Raphson (NR) method and its modifications [21]-[25]. The distribution systems are structurally weakly meshed but are typically operated with a radial structure. In this paper, the radial distribution systems solved by a straight forward two-step procedure [13] in which the branch currents are first computed (backward sweep) and then bus voltages are updated (forward sweep). In [13], the BIBC and BCBV matrices are developed based on the topological structure of distribution systems. The BIBC matrix represents the relationship between bus current injections and branch currents and the BCBV matrix represents the relationship between branch currents and bus voltages. The solution for distribution load flow can be obtained by solving (1-3) iteratively:

$$I_i^k = \left(\frac{P_{L_I} + jQ_{L_I}}{V_i^k} \right)^* \qquad (1)$$

$$[\Delta V] = [BIBC][BCBV][I] = [DLF][I] \qquad (2)$$

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \qquad (3)$$

Jacobian matrix or the Y admittance matrix is no longer necessary for this method, only the DLF matrix is necessary in solving load flow problem. Therefore, the proposed MPF algorithm can save considerable computation resources and this feature makes the proposed method suitable for online operation.

MASTER SLAVE SPLITTING METHOD FOR MIXED LOAD FLOW

As shown in Figure 1, the global power system is a typical master–slave-typed system. Here the transmission system is the master system with a detailed structure of the "generalized power supply" seen from the distribution system, while the distribution system is the slave system with a detailed structure of the "generalized load" seen from the transmission system.

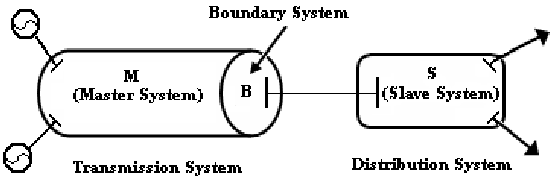


Figure 1: Global Power System with Master–Slave-Type.

In order to support distributed or parallel computation efficiently, based on the master–slave-typed physical feature of the global power system, a MSS method is developed for solving the MPF problem in this paper. In Figure 1, the load nodes in the transmission system are taken as root nodes of the distribution feeders, which make up the node set of the boundary system B, $\mathbf{C}_B$; the rest nodes of the transmission system make up the node set $\mathbf{C}_M$; the rest nodes of distribution system make up the node set $\mathbf{C}_S$. Then V of the global power system can be decomposed into:

$$V = [V_M \quad V_B \quad V_S]^T \qquad (4)$$

Where V_M, V_B and V_S denote the transmission voltage, boundary voltage and distribution voltage, respectively. According to the above characteristics of the MPF, it is obvious that a general method to deal with the large scale MPF problem should be a splitting method to support distributed or parallel computation (Figure 2).

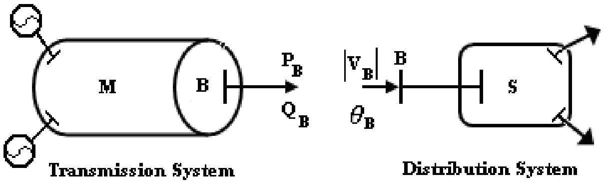


Figure 2: Illustration for the Fictitious Boundary Injection Values.

As shown in Figure 2, the MPF problem of large scale is split into a transmission system and a distribution system. The distribution systems are treated as equivalent loads in transmission system, while the transmission system is treated as equivalent power supply sources in the distribution systems. In Figure 2, fictitious boundary injection values P_B and Q_B are introduced as the intermediate variables and reflect the effect the distribution system on the transmission load flow, while V_B (magnitude and angle) is considered as reference voltage in the distribution system, which reflects the determinative effect of the transmission system on that of the distribution system. Here, per unit quantities are used for data exchange between transmission and distribution systems to meet the needs of the MPF for different per unit bases.

ONLINE DISTRIBUTED COMPUTATION

There generally exist a transmission control center and several distribution control centers in a large city. Due to geographically distributed location of these control centers, online MPF calculation should support such a geographically distributed computation. Such a distributed structure for online MPF calculation can be explained by Figure 3, where TPF and DPF denote the transmission and distribution load flows, respectively.

In Figure 3, the solutions for TPF and DPFs are performed in EMS and DMSs respectively, and EMS communicates with DMSs through WAN in each MSS iteration step. In the iterative process, EMS transfers the magnitude and angle voltage at root nodes of distribution system to corresponding DMS, while each DMS transfers the active and reactive powers of transmission system to EMS.

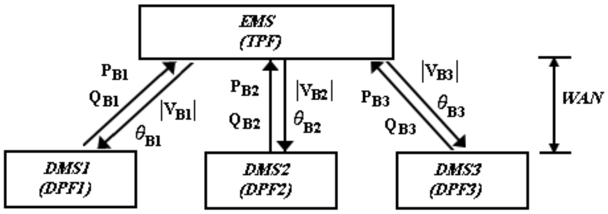


Figure 3: The distributed structure for online MPF.

The global convergence of the MPF is judged by EMS. Such a proposed distributed structure is compatible with any existing EMS and DMS with minor code modification. As a result, EMS and DMSs are combined in a unit by the online MPF, which provides a consistent real-time model for the whole transmission and distribution networks.

MSS METHOD WITH DISCUSSIONS

Based on the transmission and distribution load flows, an MSS iterative method is presented in Figures 4 and 5. The Newton-Raphson [12] and the forward/backward sweep [13] algorithms are adopted for the transmission and distribution load flows, respectively. In order to solve the MPF equations completely, inner sub-iteration needs to be introduced, and two types of detailed iterative schemes are constructed as follows:

(1) Multi-step alternating iterative (MAI) scheme: at each MSS iteration step, each of the transmission and distribution load flows is solved by several inner subiterations manually controlled, and the number of subiterations can be different for each of transmission and distribution load flows (Figure 4).

(2) Convergence alternating iterative (CAI) scheme: at each MSS iteration step, converged transmission and distribution load flows are solved, where the convergence tolerance can be controlled (Figure 5).

The two schemes described above are the same in outline with some details different. Besides the number of sub-iterations, the convergence criterions for these two schemes are different as well. The global convergence criterions of the MAI scheme can be taken as:

(1) Transmission load flow converges,

(2) Distribution load flow converges, and

(3) $\left\| V_B^{(k+1)} - V_B^{(k)} \right\|$ is less than the tolerance ε.

However, the global convergence of the CAI scheme requires only the third condition listed above, since the convergence of the transmission and distribution load flows has been achieved at each MSS iteration step. By comparison, the two schemes above are different in CPU time and in communication time. Having a less total number of sub-iterations and more interaction between TPF and DPF, the MAI scheme needs much more communication and is therefore more suitable for the parallel computation with a communication speedy enough. On the other hand, having a less number of MSS iterations and more inner iterations in TPF and DPF, the CAI scheme needs less communication and is more practical for geographically distributed computation.

The comparative results are reported in the section of test results. As shown in Figures 4 and 5, with introducing fictitious boundary injection values P_B and Q_B in the iterative process; the distribution system transfers the active and reactive powers to transmission system, while with consider V_B as reference voltage in the distribution system, the transmission system transfers the voltage (magnitude and angle) at root node to distribution system.

The global convergence of the GLF is judged by EMS. With splitting MPF problem of large scale into a transmission and lots of distribution sub-problems of small scale, the size of matrix used is very small compared to those in conventional methods (Digsilent, Neplan and etc.) and too, the Jacobian matrix or the Y admittance matrix are no longer necessary for the distribution load flow of the proposed MPF algorithm. Therefore, the proposed MPF algorithm can save considerable computation resources and these features make the proposed MPF method suitable for online operation.

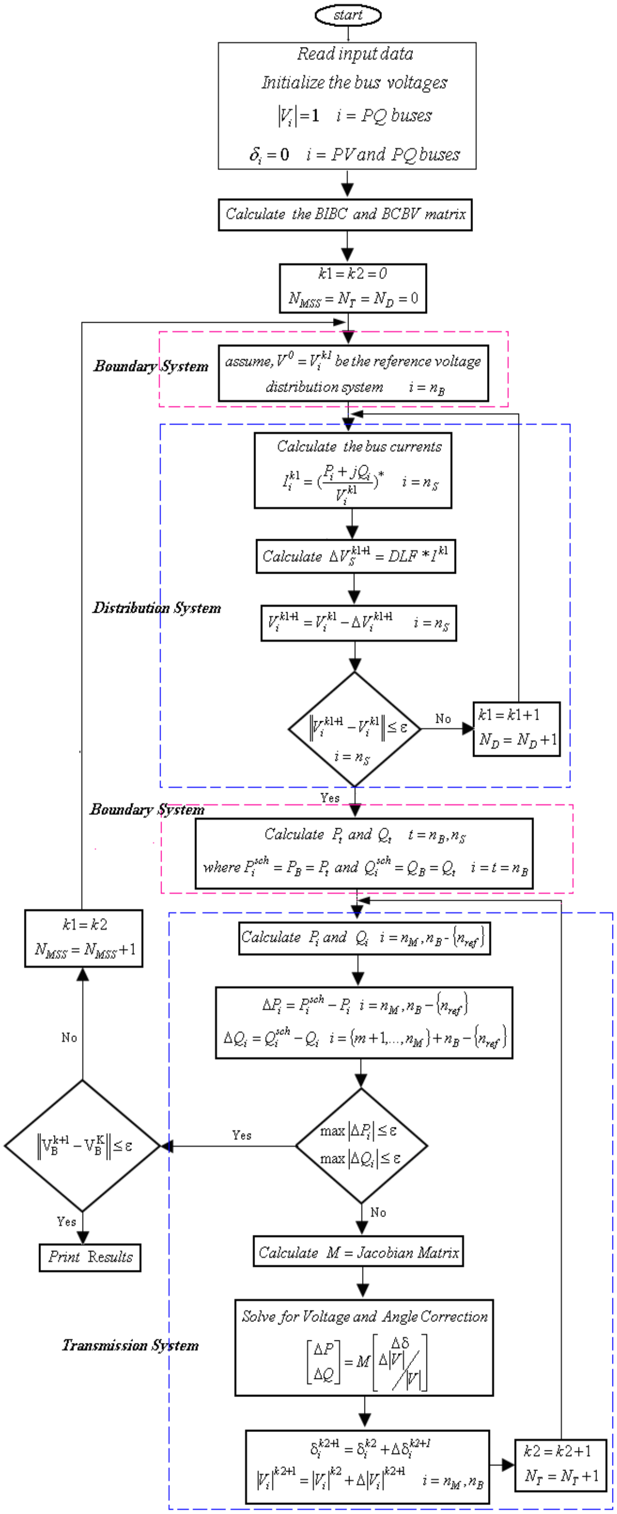


Figure 4: Flow-Chart for the Proposed Mixed Load Flow Method with MAI Scheme.

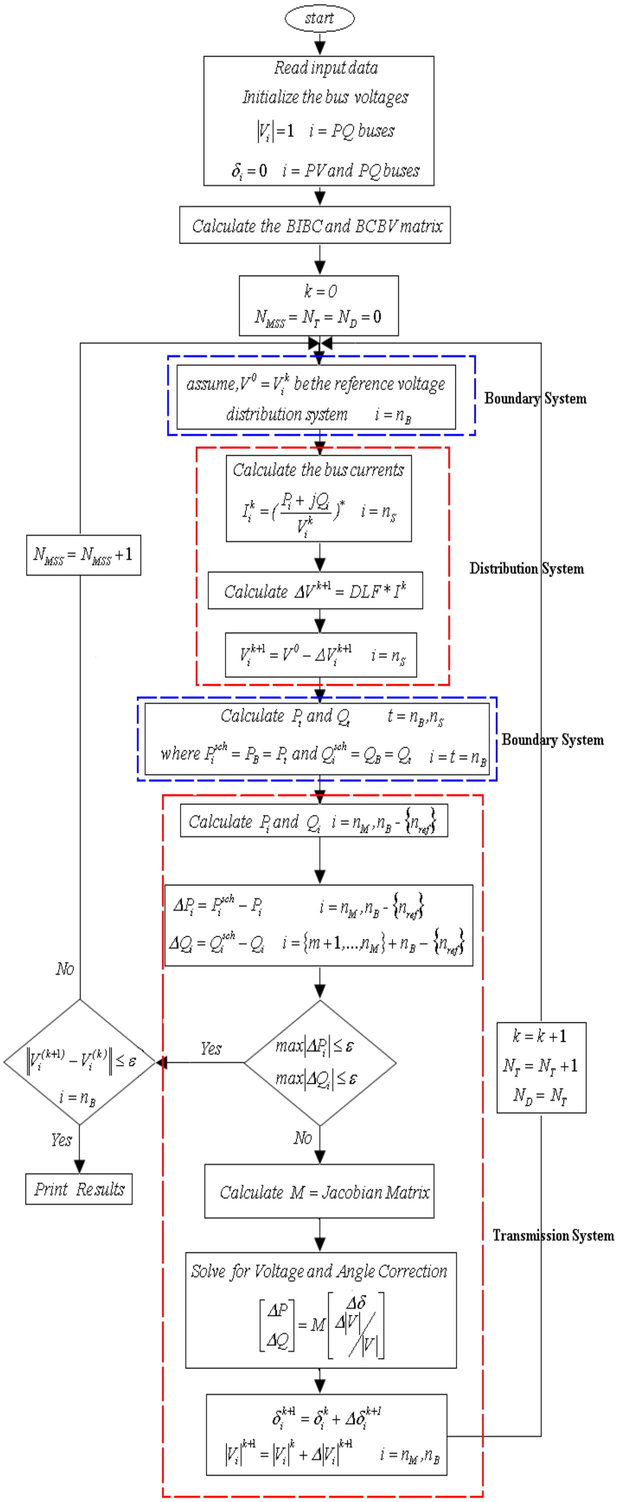


Figure 5: Flow-Chart for the Proposed Mixed Load Flow Method with CAI Scheme.

TEST RESULTS

In this section, the proposed MSS method for MPF is implemented. In order to simulate online distributed structure as shown in Fig. 3, a MPF program developed with MATLAB is separated into two parts, one is the transmission load flow and the other is the distribution one. For all of the tests reported in the following text, the convergent tolerance is 0.0001pu and the MSS method with the CAI and MAI schemes are used for tests and results both methods compared with the Digsilent load flow (Newton-Raphson).

Accuracy Comparison: For any new method, it is important to make sure that the final solution of the new method is the same as the existent method. An eight-bus test system, as shown in Figure 6 is used for comparisons. The data of the system is given in Appendix.

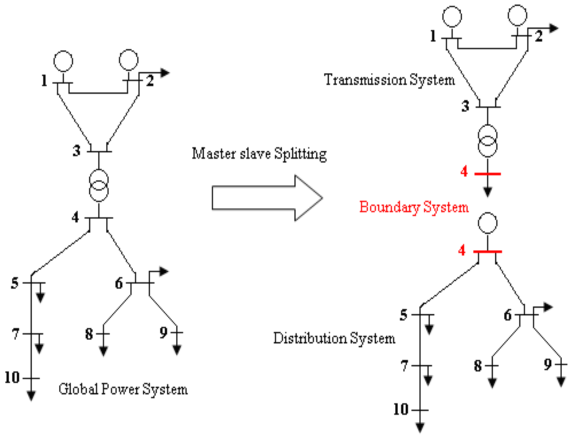


Figure 6: Eight-Bus Global Power System.

The final voltage solutions of the MSS method with the CAI and MAI schemes and the Digsilent load flow are shown in Table I.

Table 1: Final Converge Voltage Solutions.

Bus No.	Digsilent		CAI scheme		MAI scheme	
	|V| (pu.)	Angle (º)	|V| (pu.)	Angle (º)	|V| (pu.)	Angle (º)
1	1.0400	0.0000	1.0400	0.0000	1.0400	0.0000
2	1.0100	1.2618	1.0100	1.2618	1.0100	1.2618
3	1.0215	0.4141	1.0215	0.4142	1.0215	0.4142
4	1.0100	-0.4177	1.0100	-0.4174	1.0100	-0.4174
5	0.9951	-0.4446	0.9951	-0.4443	0.9951	-0.4443
6	0.9923	-0.4434	0.9923	-0.4432	0.9923	-0.4432
7	0.9810	-0.4902	0.9810	-0.4900	0.9810	-0.4900
8	0.9869	-0.4303	0.9869	-0.4300	0.9869	-0.4300
9	0.9875	-0.4646	0.9875	-0.4644	0.9875	-0.4644
10	0.9743	-0.5082	0.9743	-0.5080	0.9743	-0.5080

From Table 1, the final converged voltage solutions of the MSS method with the CAI and MAI schemes are very close to the solution of the Digsilent load flow. It means that the accuracy of the proposed MSS method is almost the same as the commonly used the Digsilent load flow.

Performance Test: In order to study the performance of the MSS method for MPF, four test global power systems, named as 5A, 5B, 5C and 5D, are constructed here. In these test systems, 5-bus test system is adopted as the transmission part, while four radial distribution systems, named as A, B, C and D, are connected into the bus number 4 of transmission system as the partial loads of transmission system (5-bus (transmission system) and 118-bus (distribution system) test systems which was acquired from the Fars Electrical Company of Iran (FEC), are used for this test. 118-bus distribution test system is chopped into various sizes for tests as shown in Table 2). For example, the test system 5A is the combination of the transmission system 5-bus and the distribution system A (60-bus).

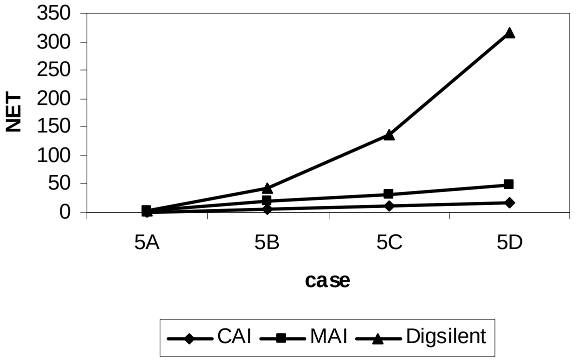
Table 2: Distribution Test Feeder.

Feeder No.	No. of Nodes
A	60
B	118
C	185
D	236

Table 3: Comparison on Performance Between The CAI and MAI Iterative Schemes for 5a Test System.

Scheme	N_{MSS}	N_T	N_D
MAI	*5*	*6*	*5*
CAI	*2*	*7*	*7*

Performances of the two proposed iterative schemes of the MSS method, CAI and MAI, are compared for 5A test system in Table 3. The number of MSS iterations for the CAI scheme is less than that for the MAI one. In Table 3, for the MAI scheme, the N_T and N_D are less than that of the CAI scheme (the N_T and N_D are the numbers of sub-iterations for the transmission and distribution systems). Because of less communication between M and S (less N_{MSS} in Table 3), it is suggested that CAI scheme be adopted if online geographically distributed computation is needed. While for the MAI scheme, with assignment of less number of sub-iterations for the transmission and distribution systems at each MSS iteration step, the total number of sub-iterations is less than that of the CAI scheme. It means the MAI scheme is usually more efficient for parallel computation with enough speedy communication.



** NET means the Normalized Execution Time.*

Figure 7: Normalized Execution Time for Mentioned Methods.

Figure 7 shows a comparison of the normalized execution time for mentioned methods. It can be seen that the CAI and MAI schemes are more efficient, especially when the network size increases. For a 241-bus system, the CAI scheme is almost 20 times faster than the Digsilent load flow. It means that the proposed method is fast and very suitable for online use.

CONCLUSION

In order to achieve a global consistent load flow solution, the transmission and distribution systems are studied as a whole in this paper. The transmission and distribution systems differ in voltage level, network topology structure, parameter of element and modeling; therefore, different load flow algorithm and base of per-unit power can be adopted to fit the different features between the transmission and distribution systems.

In the MSS method, with introducing the boundary fictitious values, the MPF problem of large scale is split into a transmission load flow and lots of distribution load flow sub-problems of small scale, As the size of matrix used is very small compared to those in conventional methods (Digsilent, Neplan, etc.) and too, from the solution technique described in the distribution load flow part of mixed load flow, the Jacobian matrix or the Y admittance matrix are no longer necessary, therefore the amount of memory used is very small, the speed is very high, and the relative speed of calculation increases with the size of the system.

The geographically distributed structure for online GSE computation is presented. Based on the MSS method, two types of detailed iterative schemes with different characteristics, namely MAI and CAI, are constructed. The proposed method was applied to several case studies and the results show the superiority of this method over the conventional ones. As this method is significantly faster than any other method developed to date, it has great potential for on-line operations.

In order to implement global optimized control between transmission and distribution systems, future studies needs to do, such as:

(1) Implementation of MPF with unbalanced distribution systems.

(2) Var. optimization for global power systems, where besides the traditional controllable variables, var output of distributed generator can also be included.

(3) Voltage stability evaluation for global power systems.

APPENDIX

Table A1: Line Data (Zbase=174.24Ω)

From	To	R p.u	X p.u
1	2	0.04	0.1
1	3	0.07	0.15
2	3	0.06	0.2
3	4	0.0	0.25
4	5	0.00689	0.00574
4	6	0.00861	0.00689
5	7	0.00918	0.00804
6	8	0.00689	0.00517
6	9	0.00746	0.00631
7	10	0.00861	0.00689

Table A2: Bus Data (S_{base}=100 MVA).

Number	P p.u	Q p.u
2	0.15	0.1
5	0.009	0.007
6	0.009	0.0065
7	0.0095	0.008
8	0.011	0.009
9	0.009	0.0065
10	0.011	0.008

P= Real MW load in p.u., Q= Reactive MVAR load in p.u.

Table A3: Transformer Data.

Voltage(Kv)	MVA	R (%)	X(%)
132/20	40	0.0	17

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